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Abstract

Molten Salt Fast Reactor (MSFR) is a new fast nuclear reactor, which is at present under memoranda and understanding (MOU) from Generation IV International Forum (GIF). In the MSFR concept, fissile material dissolved in molten fluoride salts serves as a liquid fuel in a primary loop. One of the issues that need to be addressed is the development of an extraction technique of fission products from the fuel [1]. The technique addressed here is based on the injection of helium bubbles in the molten salt in order to absorb fission products by liquid/gas mass transfer. Solid particles are expected to adsorb at bubble surfaces as well. Taking into account that molten salts, as a continuous phase, are electrically conductive, an externally applied magnetic field offers opportunities for a contactless flow control. In addition, the jump in electrical conductivities between molten salts and contaminated bubbles is expected to enhance electromagnetic separation of gaseous phase after ad/absorption processes. To address this online extraction, it is important to simulate the dynamics of bubbles flowing in a molten salt, taking into account magnetohydrodynamics of the liquid phase. Numerical simulations of the process are performed with a CFD code based on finite volume method (ANSYS FLUENT). Bubble surfaces are captured by Volume of Fluid (VOF) strategy while the electric current densities are calculated in the carrier phase by making use of the Magnetic Induction Method. In this way, we are able to describe bubble deformation due to the hydrodynamic forces and the Lorentz force, which makes the fluid to circulate mainly in planes perpendicular to the magnetic field. We investigate the transient regime required to get the terminal bubble velocity. The way the magnetic field is able to change the streamlines around a bubble is particularly investigated while varying the Hartmann number.

Key words : Molten Salt Fast Reactor ; Magnetohydrodynamics ; DC magnetic field ; Bubble dynamics ; CFD

Introduction

Bubbly flows are omnipresent in nuclear reactors processes. Fission leads to the formation of many poorly soluble neutron poisons which have thus to be eliminated. In many cases, like the Molten Salt Fast Reactor, a bubbly flows can facilitate the extraction of those nuclear wastes from the fuel. Gases have very low solubility in molten salts, to the surface of which fission products and solid particles are expected to adsorb. The idea proposed in the present investigation is then to inject bubbles in the liquid fuel and, taking into account that molten salts are electrically conductive, to apply an external magnetic field which offers opportunities for a contactless flow control. In order to represent the deformable bubble interface we used the Volume of Fluid (VOF) front capturing method, where the moving interface is implicitly represented by a scalar-indicator function defined on a fixed mesh point. An electrically isolated gas bubble does not experience a direct impact of the electromagnetic force, however the pressure and the velocity field in the surrounding conducting fluid are strongly affected, and may finally lead to a change in the bubble behaviour [2]. The coupling between the fluid flow and the magnetic field has as a result the induced of electrical currents. To study this interaction between the flow and the magnetic field it is critical to evaluate the current density due to induction. That was achieved by solving the magnetic induction equation which is derived from Ohm's law and Maxwell equations [3].

Mathematical model

Sufficient knowledge on bubble motion in a dispersed gas-liquid two-phase flow is indispensable for establishing a reliable mathematical model to describe the flow dynamics. The behaviour of bubbles moving in a liquid differs from that of solid particles in two main aspects: (i) the bubble is deformed under the action of hydrodynamic force, and (ii) an internal circulation may ensue due to momentum transfer across the gas-liquid interface. As mention before, in order to describe the deformable bubble interface we use the Volume of Fluid approach. The transport equation for the volume fraction, α, of the secondary (dispersed) phase is solved simultaneously with a single set of continuity and Navier–Stokes equations for the whole flow field. The corresponding volume fraction of the primary phase is calculated as $(1-\alpha)$. The main underlying assumptions are that the two fluids are Newtonian, incompressible, and immiscible. The governing equations can be written as:

$$\nabla \cdot \vec{U} = 0$$

$$\frac{\partial \rho_b}{\partial t} + \nabla \cdot \left(\rho_b \vec{U}\vec{U} \right) = -\nabla p + \nabla \cdot \mu_b \left(\nabla \vec{U} + \nabla \vec{U}^T \right) + \rho_b f + F_S$$

$$\frac{\partial a}{\partial t} + \nabla \cdot \left(a\vec{U} \right) = 0$$

where U is the fluid velocity, p the pressure, f the gravitational force, and Fs the volumetric representation of the surface tension force. The bulk density ρ_b and viscosity μ_b are computed as the averages over the two phases, weighted with the volume fraction α:

$$\rho_b = \rho\alpha + \rho(1-\alpha)$$

where ρ, ρ , μ and μ , are the densities and the viscosities of the two phases. In the VOF method, α is advected by the fluids.

In order to take into account the coupling between the applied electromagnetic field and the flow of the electrically conductive fluid (molten salt) the add-on magnetohydrodynamic module was implemented in the Fluent software. The induction equation can be written as:

$$\frac{\partial \vec{b}}{\partial t} + \left(\overline{U} \cdot \nabla \right) \vec{b} = \frac{1}{\mu\sigma} \nabla^2 \vec{b} + \left(\left(\overline{B_0} + \vec{b} \right) \cdot \nabla \right) \vec{U} - \left(\vec{U} \cdot \nabla \right) \overline{B_0}$$

the current density is given as:

$$\vec{j} = \frac{1}{\mu} \nabla \times \left(\overline{B_0} + \vec{b} \right)$$

For multiphase flows assuming that the electric surface current at the interface between phases can be ignored, the electric conductivity for the mixtures is given by:

$$\sigma_m = \sum_i \sigma_i v_i$$

Where σ_i and v_i are respectively the electric conductivity and volume fraction of phase i. σ_m is used in solving the induction equations.

Description of the numerical model

A new way of handling the 3D computational domain is proposed in this paper because the tracking of the bubble deformation requires a fine mesh resolution at the interface. Moreover, the MHD flow of interest here exhibit thin boundary layers: two Hartmann layers of thickness, δ=1/Ha, along the walls not aligned with the magnetic field, and two side layers along the walls parallel to the magnetic field, of thickness $\delta=1/Ha^2$, where Ha is the Hartmann number. The Ha number describes the balance between Lorentz and viscous forces:

$$\mathrm{H}a = BL\sqrt{\sigma / \mu}$$

with L, the characteristic length scale and μ, the dynamic viscosity. The external flow trapped between these boundary layers is referred to as the MHD core. In the Hartmann layers the momentum balance is largely dominated by the Lorentz force and the viscous effects, and the velocity gradients (i.e. vorticity) tend to be higher (more concentrated near the wall) as the Ha increases, thus a fine mesh required in the boundaries. The method proposed in this paper allows the accurate tracking of the liquid/gas interface and a fine meshing of the Hartmann layers with no compromise on computational limitations. In a first time, a numerical calculation is performed on a large domain with coarse mesh and only the bubble interface is characterized by a fine resolution (1400000 cells). At the time step, t=0, a spherical bubble with initial diameter 0.005 is released in the computational domain at the initial position (x_c, y_c, z_c)= (0.01, 0.008, 0.02). When the bubble reach its terminal velocity, the computational domain is cut purposely according to one third of the initial box. This time, the Hartmann and side layers can be refined, again with the adapting mesh refinement method (708000 cells), as we can see in Figure 1. Then the calculations are completed: a uniform transverse magnetic field is applied along the (transverse) x-direction and gradually increased up to Ha=500 in order to generate a significant damping effect. The exactly same calculations are performed for a vertical magnetic field imposed along the y-direction for both cases.

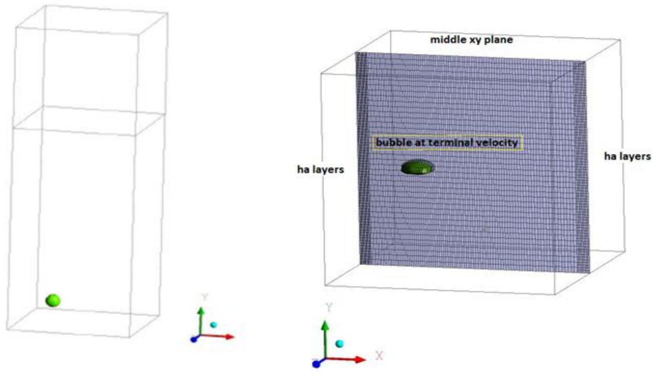

Figure 1. Initial computational domain (left) with the spherical bubble and final domain (right) including the bubble at its terminal velocity and with its equilibrium shape.

Results and discussions

In Figure 2 , the flow streamlines in the xy plane of the domain are depicted for a growing magnitude of the magnetic field (Ha=0, Ha=140 and Ha=500).

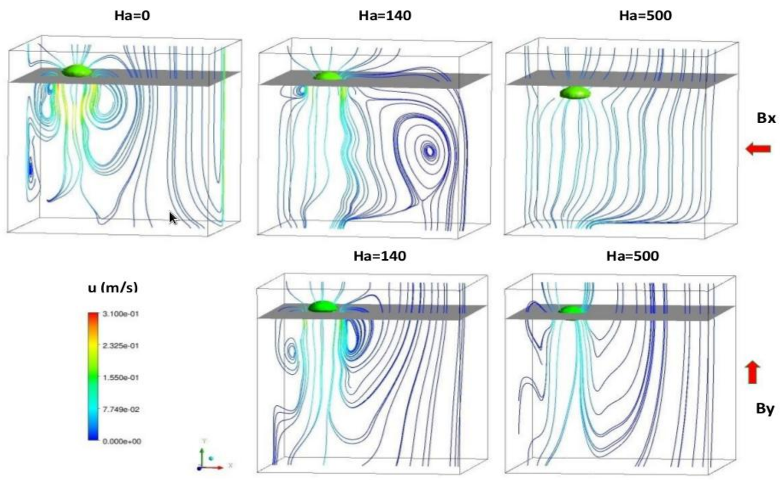

Figure 2. Streamlines plotted in the vertical xy plane in conjunction with the bubble isosurface and a fixed xz plane (y=0.1135m).

In addition the bubble isosurface is presented, in conjunction with a fixed xz plane, so as to be aware of the transversal bubble position. In our calculations, the equilibrium shape of the bubble is found ellipsoidal. A classical recirculation pattern is found at the rear of the bubble. Under the influence of the transverse magnetic field, the fluid field is expected to be strongly modified, depending on the value of the Ha number. In the case of the horizontally imposed magnetic field, the producing Lorentz force acts opposing to the flow. This electromagnetic damping caused by the Lorentz force affects the streamlines around the bubble (Ha=140), and it is found that the vorticity distribution tends to become more asymmetrical compared to the case simulated without the magnetic field. If the magnetic field becomes stronger (Ha=500), the recirculation of the flow is vanishing. That can be explained if we study the interaction parameter or Stuart number. Stuart number except from Ha number is a crucial parameter in mhd flows which gives an estimate of the relative importance of the magnetic field on the flow. For the transverse magnetic field and Ha=140 Stuart number is N=1.45. As increasing the strength of the magnetic field increase the interaction parameter also. At this point should be mentioned that the simulations with the bubbly flow under the influence of the magnetic field was performed for time $t>>\tau$ where t is the computational time and τ is the magnetic damping time defining as: in order to have clear the influence of the magnetic field on the flow. As Ha increase the bubble velocity decrease resulting in an even higher value for the Stuart number. Thus, for Ha=500 the interaction parameter is N=23.97, and the effect of the imposed magnetic field in the fluid field is much stronger. The bubble shape still remains ellipsoidal but elongates more along the x-axis aligned with the magnetic field. This is closely related to the anisotropic role of the Lorentz force. In addition, as Hartmann number increase the bubble velocity decrease, and that resulting in to lower position for the bubble, at a specific time step. When imposed a vertical magnetic field, we still have a modification of the flow and of the bubble position, but since now the Lorentz force acts perpendicular to the flow, the damping effect is less evident.

Observing Figure 3 (where the y-component and the x-component of the vorticity are plotted in the xy plane and the zy plane respectively, for Ha=140 and Ha=500, both for horizontal and vertical imposed magnetic field), for the values of small magnetic field, the asymmetrical vortex formation is obvious. In addition, the anisotropic tendency of the electromagnetic force can be clearly observed: **w**hen impose an horizontal magnetic field, for a large enough Ha number, the vorticity in the direction perpendicular to the magnetic field (y-component) is clearly damped, in contrast to the vorticity aligned with the imposed magnetic field. As already made evident in the slightly different context of the MHD turbulence, the vorticity field tends to become 2-D [4]. The MHD pseudo-turbulence, as induced by the wake vortices generated by the moving bubble, seems to become two-dimensional under the imposition of strong magnetic fields. When impose a vertical magnetic field, aligned with flow the damping effect is less evident, as mention before, and the vorticity remains.

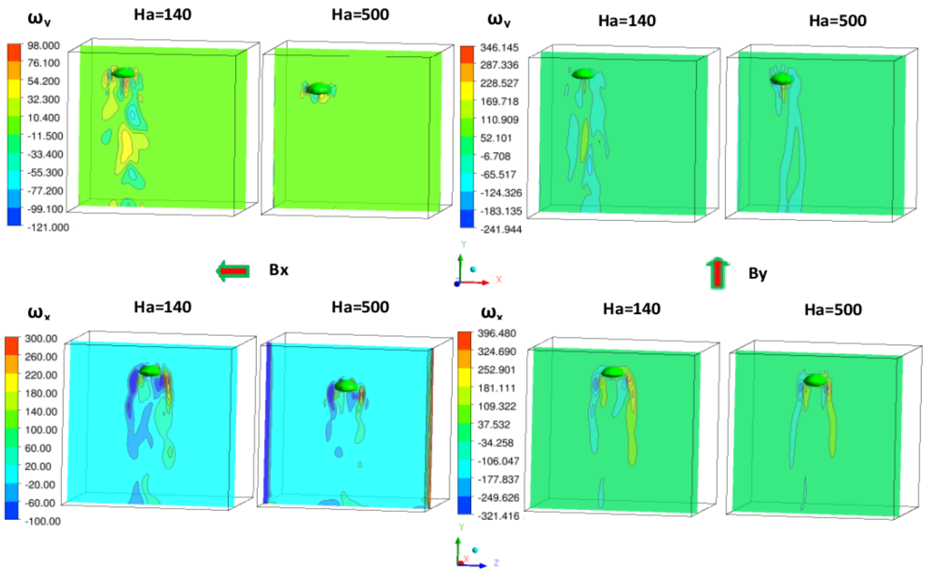

Figure.3 Contours of ω_y (at xy plane) and ω_x (at yz plane) components of vorticity for Ha=140 and Ha=500, for horizontal and vertical imposed magnetic field.

Conclusions

In the present investigation, a 3-D numerical model was used to simulate a two-phase magnetohydrodynamic flow made with an upward laminar flow of an electrically conductive molten salt and a rising helium bubble. The presence of a magnetic field perpendicular to the flow direction affects the fluid streamlines in a particular way. The 2-D anisotropy of MHD vortical flows is recovered: the vorticity in the direction perpendicular to the magnetic field is damped, while the vorticity with axis aligned along the magnetic field is not significantly affected.

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